Renewable and Sustainable Energy Reviews 15 (2011) 4212–4222

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Recent advances in biomass pretreatment – Torrefaction fundamentals and technology

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ARTICLE INFO

Article history:
Received 15 December 2010
Received in revised form 5 September 2011
Accepted 20 September 2011
Available online 25 October 2011

Keywords:
Mild pyrolysis
Kinetics
Densification
Reactor, Pelletization

ABSTRACT

Biomass and its utilization have been intimately associated to renewable energy in the recent years. However, the undesirable properties of biomass such as high moisture content and its heterogeneous nature pose a barrier to its competitiveness in the energy generation market. A viable option to overcome the issues associated with biomass feedstock is to carry out a pretreatment process called torrefaction. Torrefaction is a mild pyrolysis process carried out at 200–300 °C under inert condition. In this review, a survey of the recent research work on torrefaction is presented. The properties of biomass before and after torrefaction are discussed. Literature data are tabulated for various types of biomass utilized in the torrefaction study. A brief account on the kinetic study is outlined in the present paper. Some aspects of recent commercial development in the torrefaction process are reviewed and cited.

Contents

1. Introduction

Biomass is generally defined as the biological material derived from plant or animals as well as their waste and residues [1]. For the population in developing countries, biomass energy such as agricultural waste and crop residue is one of their prime energy sources [2]. Energy consumption by rule of thumb is closely related to economic growth. The energy demand will progressively increase with the rapid population growth and economic development. However non-renewable energy source such as fossil fuel is exhaustible. In the search for potential renewable energy sources, biomass energy is viewed as a viable option. In 2005, International Energy Agency (IEA) modeled a set of technology road map, Blue Map Scenario, to attain a 'clean, clever and competitive energy future' [3,4]. Under the Blue Map Scenario, biomass utilization is projected to elevate threefold by 2050 [5].

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doi:10.1016/j.rser.2011.09.017

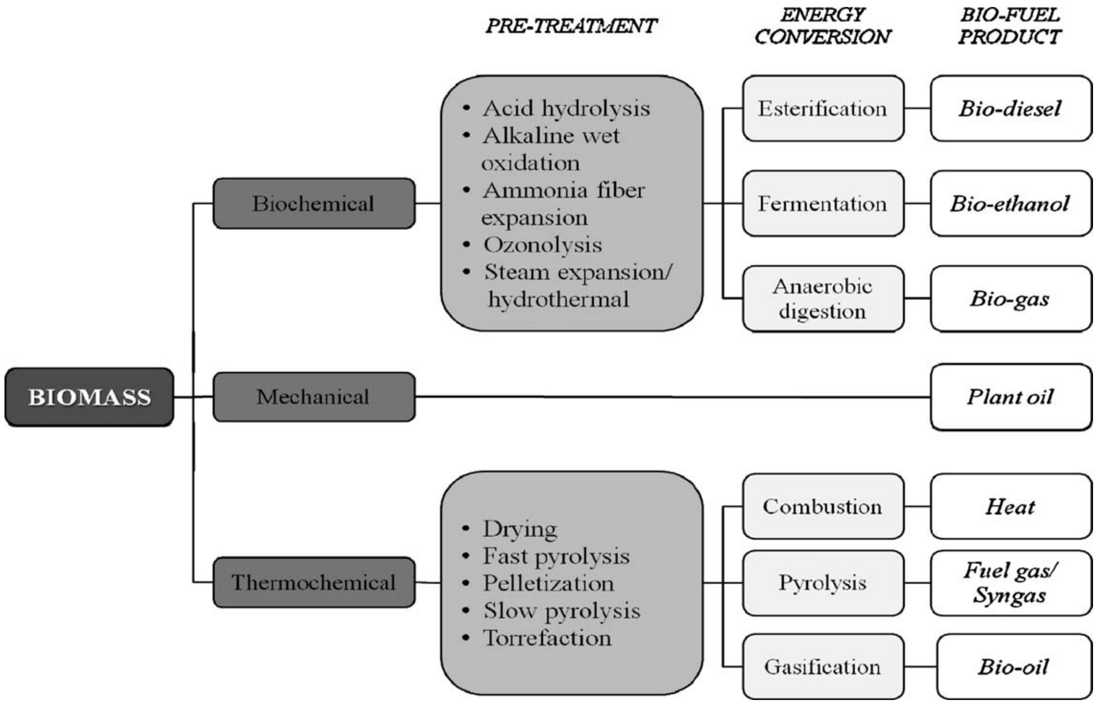


Fig. 1. Modified summary of biofuel conversion routes [21,26–28].

Biomass is typically acclaimed as a 'carbon neutral' fuel as biomass is part of the bio-cycle. The carbon dioxide produced from biomass combustion is consumed by cultivation of new crops. Biomass is a low carbon fuel and a form of sustainable fuel that offers significant reduction in net carbon emissions compared with fossil fuels [6]. In the past seven years, Brazil has avoided an estimated 83 million tons of carbon dioxide emission from the utilization of biofuel in its motor vehicles [7].

The utilization of biomass for domestic purpose has gradually expanded in both developed and developing nations in the recent years. Renewable energy source in 2009 accounted for more than half of the newly installed power capacity in Europe and USA. In the same year, biomass share in energy production exceeded oil in Sweden while Brazil invested $7.8 billion in clean energy [8]. These global trends show an encouraging future for renewable energy resources.

Renewable energy policies are among the key mechanism to overcome market barriers in promoting renewable energy. By early 2010, an estimated of 83 nations have policies promoting renewable power generation [9]. The European Union nations target 20% share of renewable energy in final energy by 2020 under the Renewable Energy and Climate Change Package [10]. China aims to achieve 15% share in its primary energy by 2020 under Medium and Long-Term Development Plan for Renewable Energy (MLTPRE) [11]. New Zealand announced a national target of 90% renewable electricity by 2025 [12].

The world production of biomass is estimated at 146 billion metric tons a year, mostly wild plant growth [13]. However, only as a small fraction is utilized for energy generation, as there are certain drawbacks in the use of raw biomass as a fuel source. Logistic cost of biomass is relatively high; due to its undesirable characteristics such as high moisture content and biological attack [14]. Technology advancement in areas such as power generation system and process selection will play a major role in assisting global nations in delivering their commitments and activities in renewable energy. In recent decade, a pre-treatment technique known as torrefaction proposed for thermal conversion process has showed positive result. This review aims to compare and compile the various works on torrefaction presented by different studies.

2. Biomass

Biomass can generally be classified as woody biomass and non-woody biomass. Woody biomass comprise mainly of products and by-products derived from the forest, woodland and trees sector. Non-woody biomass includes agricultural crops, agro-forestry residue, herbaceous products, animal waste as well as tertiary waste [2]. Biofuel have the potential to compete with fossil fuel as they share similar conversion processes. However, several issues related to the inherent properties of lignocelluloses biomass will need to be resolved.

2.1. Issues faced with biomass

Biomass like any other energy source has its advantages and disadvantages. One of the most obvious drawbacks is the heterogeneous nature of biomass. Biomass feedstock can differ considerably in term of physical, chemical and morphological characteristics. Biomass has relatively low energy density and high moisture content in its untreated form compared to fossil fuel. Higher load of biomass is required to generate the same amount of energy when compared to fossil fuel. Majority of the plant based biomass are bulky and easily subjected to fungal attack and biodegradation. The vulnerability of biomass to degradation along with the decentralized sites of most biomass sources greatly reduces the competitiveness of biomass. The presence of impurities, spread distribution in ash content, lignocelluloses content as well as factors such as climatic variability, location constraints and even cultivation practices can contribute to process variation [2,15,16]. All the above mentioned characteristics interpret into higher cost for feedstock preparation, handling, and transportation.

2.2. Biomass to energy conversion processes

Bio-fuel can be classified into three main types namely wood fuels, agro fuels and municipal by-products which is based on the source of the biomass used. Fig. 1 summarizes the technological options to convert raw biomass into convenient energy carriers such as bio-gas, liquid fuel or processed solids. The technologies can be classified into three main categories: biochemical, mechanical and thermochemical conversion. Biofuel synthesized can be grouped as three main types namely the wood fuels, agro fuel and municipal by-products [17].

Biochemical conversion utilizes biological organism and biological catalyst to convert biomass into convenient fuel such as bio-ethanol, biogas and biodiesel. Centuries-old technology of mechanical extraction is another option to obtain plant oil by physical rolling and crushing of seeds, kernel and fruits.

Thermochemical processing relies on heat and chemical catalyst to synthesize useful secondary energy. This is an attractive option for conversion of biomass to energy due to its higher efficiencies, greater versatility as well as wider range of fuel feedstock. Thermochemical conversion of biomass compared to biological conversion is a faster process. Gasification technology offers advantages such as reduced emissions, improved thermal efficiency, and the ability to generate hydrogen and other high-value fuels [18]. Gasification of biomass and coal are relatively identical as thermal decomposition yields similar gaseous products. This factor offers considerable flexibility in cost, operation and range of secondary energy. However, the disadvantages related to the nature of biomass feedstock such as the composition of more reactive ashes in biomass than in coal are among the undesirable characteristics that need to be resolved [19].

In view of the problems associated with the undesirable characteristics of raw biomass, pre-treatment offers a promising solution to enhance process efficiency prior to the main energy conversion step [20]. Torrefaction, a pre-treatment technology that requires lower treatment temperature is reported to be highly efficient for thermochemical processing and will be the main pretreatment method discussed in this paper.

3. Torrefaction

Torrefaction is a thermolysis process that subjects the feedstock to thermal treatment at relatively low temperatures of 200–300 °C in the absence of oxygen. Definition for torrefaction is commonly associated with roasting, mild pyrolysis, slow pyrolysis, and thermal pretreatment, according to its utilization. Early research work on torrefaction was mainly on wood based material such as woodchips and sawdust. In the recent years, more studies incorporate agricultural crops and agro-forestry residue. Table 1 summarize the fuel properties of different biomass. Although various sources of biomass material were investigated, similar product properties can be attained through torrefaction process such as improved energetic value, enhanced hydrophobicity and friability; which is a favored trend for thermochemical processing.

The physical and chemical properties of biomass before and after torrefaction are analyzed for the following (a) yield, (b) energy content, (c) elemental composition, (d) change in major components, (e) hydrophobicity, and (f) ease of comminution.

Table 1
Ultimate analysis, proximate analysis and higher heating value (HHV) of different biomass types.

Biomass	Ultimate analysis (wt.%)				Proximate analysis (wt.%)			HHV (MJ/kg)	Ref.
	C	H	N	O	VM	FC	A		
Woody biomass									
Banyan[b]	46.20	6.08	0.08	46.53	77.57	18.03	1.11	20.29	[21]
Beech[c,d]	47.20	6.00	0.40	45.20	84.20	15.50	0.30	18.30	[22–24]
Birch[a]	45.50	6.20	0.10	48.20	–	–	–	16.44	[25]
Eucalyptus[a]	49.00	6.10	0.20	44.60	–	–	–	19.40	[26]
Larch[d]	48.80	6.10	0.10	44.90	82.80	–	0.10	19.50	[22,23]
Lauan wood[a,d]	48.77	6.77	0.10	44.36	75.08	17.22	–	20.41	[27]
Leucaena[a,c,d]	50.10	7.40	0.70	41.80	86.10	13.10	0.80	20.30	[28]
Loblolly pine[b,d]	50.25	5.97	–	43.34	–	–	–	19.55	[29,30]
Logging residue chip[b,c]	47.29	6.20	0.42	45.19	82.17	16.07	1.77	18.79	[31]
Pine wood chip[b,c]	47.21	6.64	0.17	45.76	85.98	13.76	0.27	18.46	[31]
Sawdust[b,c]	40.85	6.17	0.03	39.07	73.15	13.02	0.38	–	[32]
Willow[c,d]	47.20	6.10	0.34	44.80	87.60	10.70	1.70	19.00	[22,23,33]
Wood briquette[b,c]	49.37	6.59	–	40.24	–	19.20	2.80	20.02	[34]
Wood pellet[a]	48.50	0.05	6.60	44.90	83.05	16.95	0.30	18.58	[35]
Non-woody biomass									
Bagasse (sugar cane)[a]	44.80	5.80	0.25	49.10	67.31	–	1.53	15.50	[25,36]
Bamboo[b]	43.84	6.05	0.07	46.53	73.56	19.94	3.51	18.70	[21]
Cotton stalk[c]	46.43	6.18	0.80	42.62	76.92	19.19	2.70	–	[37]
Empty fruit bunches (oil palm)	45.53	5.46	0.45	43.40	–	–	–	17.02	[38]
Kernel shell (oil palm)	46.68	5.86	1.01	42.01	–	–	–	19.78	[38]
Lucerne[a]	47.70	2.70	6.50	43.10	–	–	–	18.42	[35]
Mesocarp (oil palm)	46.92	5.89	1.12	42.66	–	–	–	19.61	[38]
Rape stalk	46.96	6.13	0.37	41.95	76.35	19.30	3.16	18.75	[39]
Reed canary grass[c]	48.60	6.80	0.30	37.30	82.50	12.10	5.50	19.50	[33]
Rice straw[b,c]	39.00	5.08	1.03	40.96	68.83	17.46	8.59	17.12	[39]
Rubber seed kernel	43.21	5.97	0.55	50.25	–	–	–	–	[40]
Straw[d]	44.30	5.80	0.40	42.40	79.00	–	7.10	17.40	[22,23]
Straw pellet[a]	47.50	0.63	6.40	45.50	80.80	19.20	4.60	17.80	[35]
Wheat straw[c]	47.30	6.80	0.80	37.70	76.40	17.30	6.30	18.90	[33]

C: carbon; H: hydrogen; N: nitrogen; O: oxygen; VM: volatile matter; FC: fixed carbon; A: ash; HHV: higher heating value.
[a] Dry ash free basis for ultimate analysis.
[b] Dry basis for ultimate analysis.
[c] Dry basis for proximate analysis.
[d] Dry basis for HHV.

3.1. Mass yield and energy yield

Raw biomass is deliberately subjected to limited conversion in the torrefaction process. The valuable intermediates synthesized in the process are used for energy recovery at a later stage [41]. In the torrefaction temperature range of 200–300 °C, mass loss is dominated by dehydration and devolatization in the reaction regime of hemicelluloses component [26]. Mass spectrometry analysis indicates that weight loss is accompanied by reduction in the hemicelluloses and primary lignin sections [42]. The significant mass loss at the preliminary stage of torrefaction shows reduction in the moisture of the treated biomass [43].

Mass yield and energy yield of different biomass subjected to torrefaction process is illustrated in Table 2. The mass yield of torrefied biomass can vary from 24% to 95% of its original weight. Conversion rate of agricultural residues is comparatively higher than woody biomass due to its higher hemicelluloses content, thus resulting in lower mass yield [33,39,44]. Studies show that the polymeric structure of the feedstock will affect the reactivity of torrefaction reaction [44,45]. Higher content of xylan, the main fraction in hemicelluloses fraction, will increase the rate of reaction [44]. Increasing the torrefaction temperature and residence time will improve the higher heating value (HHV) of biomass. HHV increment of torrefied biomass was in the range of 1–58% for the various biomasses as displayed in Table 2. Net calorific values of woody and non-woody biomass are in the range of 18–26 MJ/kg and 12–25 MJ/kg, respectively.

Energy yield based upon the mass yield and calorific value and can be viewed as an indicator of the amount of energy lost during torrefaction. Energy yield for woody biomass subjected to torrefaction temperatures below 250 °C is above 95% except for Lucerne wood (88%). As torrefaction temperature increase to above 250 °C, energy yield spreads from 55% to 98%. Non-woody biomass generally has a wider spread in energy yield compared to woody biomass, ranging from 29% to 98%, due to the higher variation in volatile matter and hemicelluloses fraction [39]. The effect of torrefaction duration is reported to be less significant compared to temperature and the ideal operating condition is either at a lower temperature regime or higher torrefaction temperature coupled with shorter duration to minimize energy loss [22,46].

3.2. Ultimate and proximate analysis

The ultimate analyses data of biomass samples subjected to torrefaction were obtained from the literature and presented in Table 3. Generally, the elemental analysis demonstrates an increase in fixed carbon content as torrefaction conditions intensifies. The higher loss in oxygen and hydrogen compared to carbon is highly related to the increase in energy value of the biomass [16,24]. The characterization of the elemental improvement in biomass relative to fossil fuel is vital in the investigation of biofuel application. Van Krevelen diagram is a graphical illustration of the elemental changes in biomass. The atomic hydrogen to carbon ratio index is plotted against the atomic oxygen to carbon ratio in Van Krevelen diagram.

Fig. 2(a) illustrates the atomic ratio of coal samples and untreated biomass samples. The dotted straight lines in the diagram represents the dehydration reaction pathway. Prior to torrefaction, the woody biomass samples have a H:C ratio of 1.6 and O:C ratio of 0.75. For torrefaction temperature range of 200–250 °C in Fig. 2(b), the H:C ratio drops to approximately 1.5 and O:C ratio is 0.6. At torrefaction temperature above 250 °C in Fig. 2(c), the van

Table 2
Mass yield, energy yield and higher heating value of torrefied biomass; only data for 0.5 h and 1.0 h duration are presented.

Biomass	*t* (h)	*T* (°C)	MY (wt.%)	EY (wt.%)	HHV (MJ/kg)	Ref.	Biomass	*t* (h)	*T* (°C)	MY (wt.%)	EY (wt.%)	HHV (MJ/kg)	Ref.
Woody biomass													
Birch	1.0	250	85.50	97.93	18.83	[25]	Empty fruit bunches (oil palm)	1.0	220	43.16	43.54	17.17	[38]
Logging residue chip	0.5	225	88.00	92.68	19.79	[31]		1.0	250	36.98	38.39	17.67	
	0.5	250	81.00	91.43	21.21			1.0	300	24.18	29.00	20.41	
	0.5	275	70.00	82.07	22.03		Kernel shell (oil palm)	1.0	220	77.44	73.80	18.85	[38]
	0.5	300	52.00	73.09	26.41			1.0	250	73.83	71.18	19.07	
Leucaena	0.5	200	91.00	94.14	21.00	[28]		1.0	300	71.27	78.12	21.68	
	0.5	225	86.50	90.33	21.20		Lucerne	1.0	230	87.00	88.28	18.69	[35]
	0.5	250	73.00	76.24	21.20			1.0	250	81.60	83.06	18.75	
	0.5	275	54.50	61.21	22.80			1.0	280	71.60	77.31	19.89	
Pine	0.5	225	89.00	93.92	19.48	[31]	Mesocarp (oil palm)	1.0	220	63.08	61.21	19.03	[38]
	0.5	250	82.00	89.20	20.08			1.0	250	60.04	58.91	19.24	
	0.5	275	73.00	86.29	21.82			1.0	300	52.45	59.30	22.17	
	0.5	300	52.00	71.49	25.38		Peanut husk	1.0	250	72.50	81.02	16.35	[36]
Pine	1.0	230	92.40	96.51	18.07	[25]		1.0	270	67.00	85.18	18.60	
	1.0	250	88.20	94.37	18.51			1.0	300	55.75	72.25	18.96	
	1.0	280	78.10	93.90	20.80		Rape stalk	0.5	200	63.29	65.82	19.50	[39]
Willow	0.5	230	95.10	96.05	20.20	[33]		0.5	250	38.26	41.01	20.10	
	0.5	250	89.60	92.29	20.60			0.5	300	25.30	29.13	21.59	
	0.5	270	79.80	85.39	21.40		Reed canary grass	0.5	250	83.00	85.13	20.00	[33]
	0.5	290	72.00	78.84	21.90			0.5	270	72.00	76.80	20.80	
Wood briquette	0.5	220	94.00	95.91	20.43	[34]		0.5	290	61.50	68.75	21.80	
	0.5	250	74.00	78.39	21.21		Rice straw	0.5	200	59.84	59.98	17.16	[39]
	0.5	270	56.00	63.70	22.77			0.5	250	40.32	42.46	18.03	
Wood briquette	1.0	220	90.00	94.36	20.99	[34]		0.5	300	36.57	39.90	18.68	
	1.0	250	65.00	71.63	22.06		Sawdust	1.0	250	67.25	72.48	19.55	[36]
	1.0	270	54.00	61.99	22.98			1.0	270	59.50	67.14	20.47	
Non-woody biomass								1.0	300	42.00	55.10	23.80	
Bagasse (sugarcane)	1.0	230	87.50	96.42	17.08	[25]	Straw pellets	1.0	230	95.00	95.53	17.90	[35]
	1.0	250	78.90	92.03	18.08			1.0	250	90.00	92.07	18.21	
	1.0	280	68.60	82.90	18.73			1.0	280	79.90	89.87	20.02	
Cotton stalk	0.5	200	63.89	83.44	23.94	[37]	Wheat straw	0.5	200	47.56	56.02	19.84	[37]
	0.5	250	33.80	45.30	24.57			0.5	250	41.24	51.05	20.85	
	0.5	300	30.04	41.02	25.03			0.5	300	31.61	40.67	21.67	

t: time; T: temperature; MY: mass yield; EY: energy yield; HHV: higher heating value.

Table 3
Ultimate analysis of different biomass for torrefaction duration of 0.5 h and 1.0 h.

Biomass	t (h)	T (°C)	C (wt.%)	H (wt.%)	N (wt.%)	O (wt.%)	Ref.	Biomass	t (h)	T (°C)	C (wt.%)	H (wt.%)	N (wt.%)	O (wt.%)	Ref.
Woody biomass								Willow	0.5	230	50.70	6.20	0.20	39.50	[33]
Banyan[b]	1.0	230	53.55	6.84	0.15	37.08	[21]		0.5	250	51.70	6.10	0.20	38.70	
	1.0	260	60.73	6.46	0.18	28.52			0.5	270	53.40	6.10	0.20	37.20	
	1.0	290	66.21	6.22	0.15	22.57			0.5	290	54.70	6.00	0.10	36.40	
Beech	1.0	240	51.70	5.40	0.00	42.90	[24]	Willow [b]	1.0	230	56.59	6.41	0.14	34.21	[21]
	1.0	260	54.40	5.20	0.00	40.40			1.0	260	65.16	7.10	0.23	24.33	
Eucalyptus[a]	0.5	240	53.10	6.10	0.10	40.60	[26]		1.0	290	67.55	7.06	0.22	20.92	
	0.5	260	55.70	5.80	0.10	38.30		**Non-woody biomass**							
	0.5	280	57.80	5.50	0.20	35.30		Bagasse (sugarcane)	1.0	230	48.60	5.60	0.25	45.50	[25]
Eucalyptus[a]	1.0	240	53.00	5.90	0.10	40.90	[26]		1.0	250	50.60	5.60	0.30	43.50	
	1.0	260	55.40	5.80	0.10	38.60			1.0	280	52.80	5.30	0.39	41.50	
	1.0	280	63.50	5.30	0.20	30.90		Bamboo [b]	1.0	230	56.68	6.18	0.17	32.42	[21]
Lauan wood[a]	0.5	220	54.33	6.99	0.15	38.53	[27]		1.0	260	62.26	6.29	0.13	24.64	
	0.5	250	64.40	6.37	0.12	29.11			1.0	290	64.58	6.56	0.16	19.31	
	0.5	280	64.76	5.92	0.44	28.88		Empty fruit bunches (oil palm)	1.0	220	46.75	4.68	1.27	41.42	[38]
Lauan wood[a]	1.0	220	54.91	6.85	0.17	38.07	[27]		1.0	250	47.07	4.95	1.35	42.24	
	1.0	250	65.37	6.06	0.16	28.41			1.0	300	49.56	4.38	1.27	43.19	
	1.0	280	65.76	5.47	0.16	28.61		Kernel shell (oil palm)	1.0	220	45.87	6.31	0.40	43.07	[38]
Logging residue chip[b]	0.5	225	50.15	6.10	0.30	42.74	[31]		1.0	250	51.89	5.71	0.47	38.50	
	0.5	250	54.91	5.87	0.31	40.96			1.0	300	54.21	5.08	0.50	36.66	
	0.5	275	53.24	5.39	0.30	40.12		Lucerne	1.0	230	48.70	3.20	6.30	41.80	[35]
	0.5	300	66.07	4.92	0.48	27.34			1.0	250	50.70	3.20	5.70	40.40	
Leucaena[a]	0.5	200	51.70	7.10	0.70	40.50	[28]		1.0	280	54.10	3.60	5.30	37.00	
	0.5	225	52.40	7.10	0.70	39.80		Mesocarp (oil palm)	1.0	220	46.93	5.50	1.83	43.30	[38]
	0.5	250	53.00	6.40	0.70	39.90			1.0	250	47.70	5.20	1.74	40.18	
	0.5	275	57.20	5.50	0.80	36.50			1.0	300	48.60	4.87	2.14	40.03	
Pine[b]	0.5	225	49.47	6.07	0.15	44.03	[31]	Reed canary grass	0.5	230	49.30	6.50	0.10	–	[33]
	0.5	250	51.46	5.86	0.14	42.02			0.5	250	50.30	6.30	–	37.00	
	0.5	275	54.91	6.20	0.20	38.17			0.5	270	52.20	6.00	0.10	37.30	
	0.5	300	63.67	5.58	0.20	29.99			0.5	290	54.30	6.10	0.10	36.30	
Pine	1.0	230	49.70	5.90	0.06	44.30	[25]	Straw pellets	1.0	230	47.80	0.66	6.30	45.20	[35]
	1.0	250	50.90	5.80	0.06	43.20			1.0	250	49.00	0.79	6.10	44.10	
	1.0	280	56.40	5.50	0.06	38.00			1.0	280	52.80	0.85	6.10	40.30	
Sawdust[b]	0.5	230	45.92	5.20	0.53	37.01	[32]	Wheat straw	0.5	230	48.70	6.30	0.70	–	[33]
	0.5	250	47.16	5.01	0.55	35.52			0.5	250	49.60	6.10	0.90	35.60	
	0.5	270	50.67	4.77	0.65	30.81			0.5	270	51.90	5.90	0.80	33.20	
	0.5	290	52.22	4.41	0.71	27.72			0.5	290	56.40	5.60	1.00	27.60	

t: time; T: temperature; C: carbon; H: hydrogen; N: nitrogen; O: oxygen.
[a] Dry and ash free basis for ultimate analysis.
[b] Dry basis for ultimate analysis.

Krevelen plot suggests that torrefaction shifts the elemental ratios of biomass towards that of coal. During the process of torrefaction, changes have been accounted to the release of carbon dioxide as well as water, favorable for gasification and combustion [14,36,47]. Comparing the three plot in Fig. 2, it can be noted the decomposition mechanism of torrefaction involves significant dehydration as the changes in the H:C and O:C atomic ratios of biomass follows the dehydration pathway.

Table 4 shows that fixed carbon content increases while volatile content decreases as torrefaction temperature and residence time intensifies across different biomass. The disintegration of oxygen functional group has been accounted for the change of the proximate analysis compounds [28]. Volatile loss for wheat straw, rice husk, logging wood chip, pine and sugarcane bagasse are around 25% which is relatively higher compared to the remaining biomass. Catalytic effect of inorganic mineral matter in the biomass has been accredited for the higher loss in volatile matter [43]. Ash content generally increases from 0.1 to 12% after torrefaction, though comparatively lower compared to the change in fixed carbon content (0.9–29.0%). As the ash content is inherent to the feedstock chosen for torrefaction, the initial ash content of feed has relative impact on the resulting torrefied product [33,36,48].

3.3. *Reduced moisture affinity*

One of the main disadvantages of biomass has been related to the presence of moisture which penalizes its performance especially in thermochemical processes. Hydrophobic property of torrefied product is generally examined via: (a) immersion test, or (b) equilibrium moisture content (EMC) study. For immersion test, treated and untreated biomass is submerged in water for a fixed duration of time. Hydrophobicity is judged based on the total moisture absorption of sample in weight basis. Equilibrium moisture content applies static desiccator technique using saturated salt solution to attain required humidity. Coupled with water bath, an environment with constant humidity and temperature can be achieved. Tested sample attains equilibrium state when measured weight is constant for targeted duration.

Moisture absorption of thermal treated sample is comparatively lower than untreated biomass using immersion test [34,36]. However the trend moisture absorption of torrefied sample with respect to torrefaction parameter differs in both cases. Moisture absorption is lower for biomasses that were torrefied at higher temperature [34,36]. The effect of torrefaction on equilibrium moisture content was examined across relative humidity range of 11.3–97.0% [29,49]. Analogous results are obtained for the immersion test, whereby pretreated biomass has reduced affinity for moisture compared to raw sample. An EMC model was fitted to the measured data and the moisture adsorption capacity was concluded to reduce with increased torrefaction temperature [49,50]. In the torrefaction temperature regime, water is one of the main products release along with volatiles. Physical drying of biomass is first initiated at approximately 100 °C whereby the free water in biomass feedstock is liberated. Light organic volatiles are evolved in the post drying steps as the organic molecules dehydrate. As the temperature gradually increases to the excess of 200 °C, bound water in

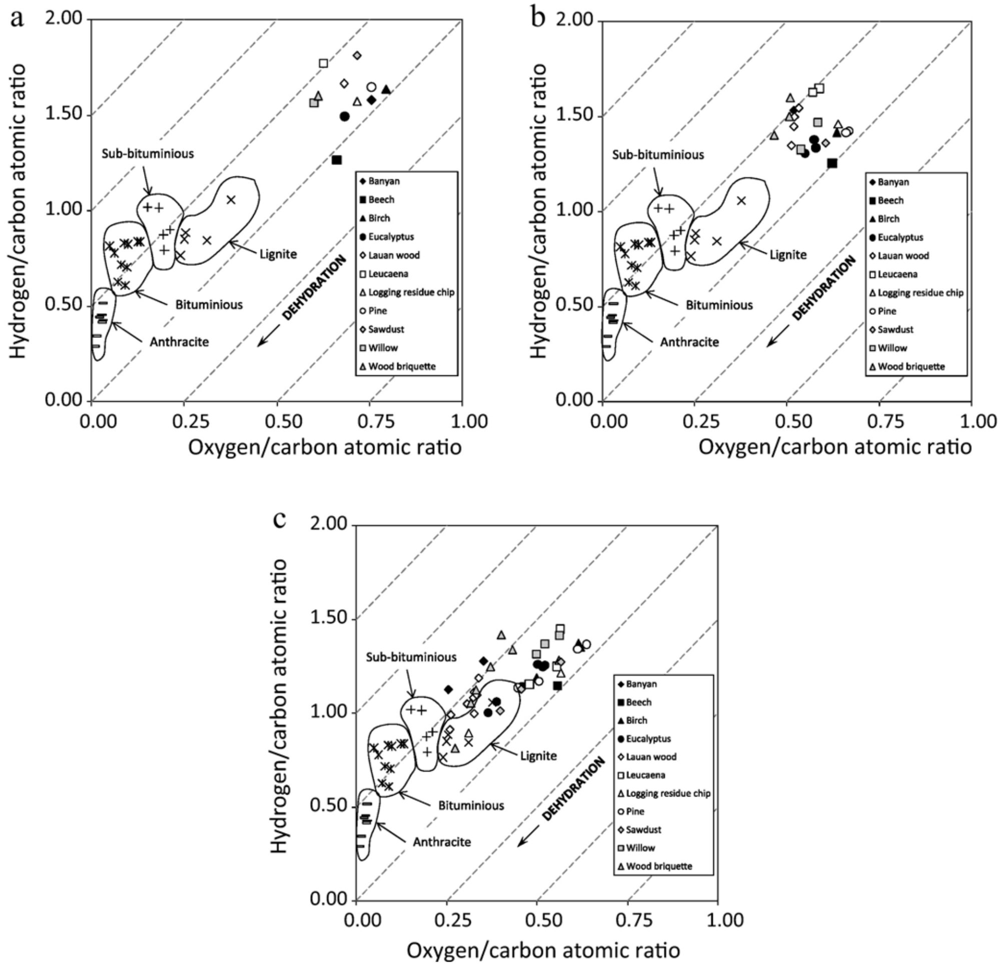


Fig. 2. Van Krevelen plot (a) coal sample and untreated biomass, (b) coal samples and torrefied biomass at 200–240 °C and (c) coal samples and torrefied biomass at and above 250 °C.

biomass is released [16,33]. Depolymerization of long polysaccharide chains shortens the polymeric structure of biomass, mainly from the hemicelluloses fractions [16]. This is coupled with limited devolatization and carbonization of the lignin and cellulose. During torrefaction, the breakage of the hydroxyl group on the cellulose microfibrils monomers introduces hydrophobic properties to torrefied biomass [51]. This non-reversible reaction preserves the quality of the product as the torrefied biomass molecules are non-polar and prolongs the storage duration [43]. Consequently, combustion behavior of torrefied biomass becomes more exothermic and ignition time is shorter compared to untreated biomass [33]. The aforementioned improved properties of torrefied biomass are favorable for transportation, utilization and storage of biomass because of its increased stability and durability.

4. Grindability

Through decomposition of the hemicelluloses coupled with depolymerization of cellulose and thermal softening of lignin, the orientation of microfibrils is displaced during torrefaction. The cell wall in the biomass sample is greatly weakened after torrefaction [37]. The increased brittleness and friability introduced by torrefaction improves the grindability of biomass. The ease of comminution in torrefaction studies is widely examined through the particle distribution of milled samples after being distributed according to its size range. Generally, grindability of biomass improves after torrefaction based on the increased percentages of fine particle as torrefaction condition are raised [26,27,39]. An alternative method is the particle distribution study is coupled with grinding energy consumption in examining the grindability [47,52]. Specific energy consumption for treated biomass are reduced as much as 10 times after torrefaction [31]. Literature defines the improved grindability and reduced energy consumption in comminution to a two stage mechanism [52].

The improved ease to grind biomass is attributed to the dehydration and physical transformation of lignin at lower temperature. Subsequently, the second stage is the thermal degradation of the cell wall biomass as discussed earlier that contributes to the higher percentage of fine particle after torrefaction [52]. The standard Hardgrove Grindability Index (HGI) used to analyze the grindability of coal had been studied in literature for torrefied biomass sample [47]. The modified HGI study adopted volumetric measurement for the sample to be milled in place of mass measurement as biomass are of lower density compared to coal. Although treated sample achieves similar grindability to reference coal samples for extended torrefaction parameter, literature indicate that volumetric HGI may underestimate the grinding property of biomass as large fraction of biomass were removed in the pre-milling step [47]. The result obtain from volumetric HGI is not representative of all samples, although a general improvement in the grindability of torrefied biomass has been observed.

4.1. Kinetics

Reaction kinetics studies the rate of chemical reaction as well as factors affecting the speed of reaction. In the establishment

Table 4
Proximate analysis of biomass after torrefaction for torrefaction duration 0.5 h and 1.0 h.

Biomass	*t* (h)	*T* (°C)	VM (wt.%)	FC (wt.%)	A (wt.%)	Ref.
Woody biomass						
Beech[a]	1.0	240	80.60	19.20	0.35	[24]
	1.0	260	75.70	24.20	0.40	
Eucalyptus grandis (bark)[a]	1.0	220	65.70	29.50	4.80	[48]
	1.0	250	63.80	32.30	3.90	
	1.0	280	53.00	42.90	4.10	
Eucalyptus grandis (wood)[a]	1.0	220	77.50	22.30	0.20	[48]
	1.0	250	71.40	28.30	0.30	
	1.0	280	67.50	32.30	0.20	
Eucalyptus saligna (bark)[a]	1.0	220	73.60	22.70	3.60	[48]
	1.0	250	65.60	29.70	4.60	
	1.0	280	57.90	35.60	6.50	
Eucalyptus saligna (wood)[a]	1.0	220	77.10	22.70	0.20	[48]
	1.0	250	72.50	27.20	0.30	
	1.0	280	67.10	32.80	0.10	
Leucaena[a]	0.5	200	85.30	14.00	0.70	[28]
	0.5	225	84.30	14.90	0.80	
	0.5	250	82.20	16.90	0.90	
	0.5	275	73.80	24.90	1.30	
Logging residue chip[a]	0.5	225	80.75	17.90	1.37	[31]
	0.5	250	78.16	20.37	1.49	
	0.5	275	71.44	26.69	1.88	
	0.5	300	52.92	44.76	2.32	
Pine[a]	0.5	225	84.78	14.95	0.27	[31]
	0.5	250	82.52	17.24	0.25	
	0.5	275	76.40	23.26	0.35	
	0.5	300	58.72	40.85	0.43	
Sawdust[a]	0.5	230	69.10	19.84	8.62	[32]
	0.5	250	64.79	23.74	9.21	
	0.5	270	57.07	30.15	10.63	
	0.5	290	49.68	35.71	12.54	
Willow[a]	0.5	230	82.10	16.10	1.80	[33]
	0.5	250	79.80	18.40	1.90	
	0.5	270	79.30	18.60	2.10	
	0.5	290	77.20	20.50	2.30	
Wood briquette [a]	0.5	220	75.20	18.20	6.60	[34]
	0.5	250	65.20	27.00	7.80	
	0.5	270	55.70	34.60	9.70	
Wood briquette [a]	1.0	220	74.60	19.00	6.40	[34]
	1.0	250	65.00	27.20	7.80	
	1.0	270	52.10	38.20	9.70	
Non-woody biomass						
Bagasse (sugarcane)	1.0	250	65.49	26.82	2.89	[36]
	1.0	270	60.03	32.97	2.91	
	1.0	300	40.44	51.63	4.12	
Cotton stalk[a]	0.5	200	44.43	41.89	8.44	[37]
	0.5	250	36.13	44.48	12.69	
	0.5	300	31.16	48.00	14.74	
Peanut husk	1.0	250	50.86	20.05	24.48	[36]
	1.0	270	45.47	23.81	26.84	
	1.0	300	38.82	23.86	33.77	
Reed canary grass[a]	0.5	250	80.30	13.30	6.40	[33]
	0.5	270	76.60	16.10	7.30	
	0.5	290	70.50	21.30	8.30	
Rice husk	1.0	250	54.76	19.73	21.56	[36]
	1.0	270	49.99	21.75	24.57	
	1.0	300	30.04	35.97	31.32	
Water hyacinth	1.0	250	31.33	5.84	58.98	[36]
	1.0	270	32.15	13.09	51.19	
	1.0	300	24.82	13.86	58.50	
Wheat straw[a]	0.5	250	77.00	15.60	7.40	[33]
	0.5	270	65.20	26.50	8.40	
	0.5	290	51.80	38.00	10.20	

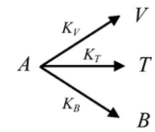
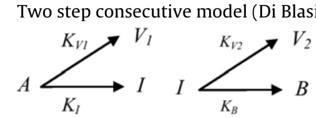
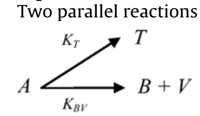
t: time, T: temperature, VM: volatile matter, FC: fixed carbon, A: ash.
[a] Dry basis for proximate analysis.

of appropriate thermochemical conversion processes and design of the operational equipments, fundamental knowledge of the reaction mechanism and kinetics is vital. Mathematical model examined for torrefaction kinetic studies were mainly models derived for biomass pyrolysis process [53–55]. Biomass is typically regarded as composed of mainly hemicelluloses, cellulose and lignin. Studies have shown that the biomass pyrolysis process can be sub-divided into four main regimes [56,57]. Moisture evolution is the main reaction mechanism at low temperature below 220 °C. Hemicelluloses degradation follows at temperature above 200 °C with lignin decomposing slowly in the background starting from around 160 °C until 900 °C. Cellulose decomposition continues from 200 °C to 400 °C. In literature, torrefaction has been defined as a mild pyrolysis process which improves the fuel properties of biomass [26,44]. Reviewing the torrefaction temperature range of 200–300 °C, the main reaction activity comprise of moisture evolution, hemicelluloses decomposition with limited degradation of lignin and cellulose. Table 5 summarizes the kinetic models applied for the torrefaction conditions. One step global model is the simplest form of pyrolysis kinetic model whereby overall biomass thermal degradation is modeled as a single step first order reaction. The one step global model described in Table 5 was examined for the anhydrous weight loss kinetic of two woody biomass (spruce and beech) subject to torrefaction process [53]. Good fitting between the calculated and experimental anhydrous weight loss (R^2 of 0.961–0.993) was reported. The authors assumed the thermal decomposition of spruce and beech to be similar and adopted the activation energy of 92.0 kJ/mol, as defined in literature for model fitting [58]. The resulting kinetic constant fits the predicted reactivity of hardwood versus softwood; beech and spruce were 1.02 × 105 kg/kg s and 2.88 × 105 kg/kg s, respectively. However in practical application, this single step model is not applicable for the prediction of product yield due to the assumption of fixed ratio of pyrolytic products [59].

Several studies adopted a two step consecutive model, the Di Blasi–Lanzetta model for the weight loss kinetics of woody biomass [22,53,55,59]. An intermediate reaction product accounting for secondary devolatization reactions is introduced in the model. For the temperature range of 230–300 °C, the kinetics of torrefaction reactions can be well described by two consecutive first order reactions, depicting hemicelluloses degradation followed by cellulose decomposition [55]. Correlation using the Di Blasi–Lanzetta model was reported to fit better (R^2 value of 0.986–0.987) than the single step model for both hardwood and softwood [53]. The improved fitting of model is attributed to the two step consecutive model taking account of the intermediate pseudo-component [53,55]. Based on the kinetic parameters derived for the willow sample, the rate of the first reaction is higher than the second reaction [60]. Within the torrefaction temperature regime, thermal decomposition continues under an extended duration. Literature accounts this phenomenon to the decomposition of cellulose and lignin possible catalyzed by the inorganic substance or the liquid and gaseous by-products [60].

Thermal degradation of the lignocelluloses was proposed to be three independent overlapping reactions of hemicelluloses, cellulose and lignin [58]. The model was studied in the torrefaction of beech and spruce [53]. In this model, the hemicellulose breaks down following the mentioned Di Blasi–Lanzetta model. Lignin disintegration adopts the single step model. Cellulose decomposition follows the modified Broido–Shafizadeh model represented by two competitive parallel reactions as shown in Table 5 [61].

Table 5
Kinetic mechanism applied for torrefaction studies.

Biomass	Temperature (°C)	Kinetic model
Spruce and beech [53]	220–260	One step global model $A \xrightarrow[K_B]{} B + V$
Wood [54], wood log and briquettes [63]	130–280	Three parallel reactions model (Shafizadeh and Chin model)  Kinetic parameters used by Ratte et al. [54]: $E_{A\|V}$ = 88.6 kJ/mol $K_V = 8.607 \times 10^5$ kg/kg s $E_{A\|T}$ = 112.7 kJ/mol $K_T = 2.475 \times 10^8$ kg/kg s $E_{A\|B}$ = 106.5 kJ/mol $K_B = 4.426 \times 10^7$ kg/kg s Kinetic parameters used by Felfli et al. [63]: $E_{A\|V}$ = 140.0 kJ/mol $K_V = 1.30 \times 10^8$ kg/kg s $E_{A\|T}$ = 133.0 kJ/mol $K_T = 2.00 \times 10^8$ kg/kg s $E_{A\|B}$ = 121.0 kJ/mol $K_B = 1.08 \times 10^7$ kg/kg s
Willow [22,55], spruce and beech [53]	220–300	Two step consecutive model (Di Blasi–Lanzetta model)  Kinetic parameters from Bergman et al. [22]: $E_{A\|I}$ = 76.0 kJ/mol $K_I = 2.48 \times 10^4$ kg/kg s $E_{A\|V_1}$ = 114.2 kJ/mol $K_{V_1} = 3.23 \times 10^7$ kg/kg s $E_{A\|B}$ = 151.7 kJ/mol $K_B = 1.10 \times 10^{10}$ kg/kg s $E_{A\|V_2}$ = 151.7 kJ/mol $K_{V_2} = 1.59 \times 10^{10}$ kg/kg s
Spruce and beech [53]	220–260	Two parallel reactions model (Broido–Shafizadeh model) 

Where *A* is the biomass, *B* is the solid product, *I* is the intermediate compounds, *T* is the tar, and *V* is the volatiles.

Good correlation was obtained between the model and experimental data. However the reactivity predicted for the beech and spruce contradicts with the experimental observation. As the lignocellulosic constituents of biomass samples are not wholly independent in thermal decomposition, the degradation of the hemicelluloses and cellulose is proposed to be modeled with the introduction of pseudo-components to incorporate the possible interaction between the components [53].

For the torrefaction of large biomass particle such as wood log and briquettes, Shafizadeh and Chin model was adopted for the thermal degradation reaction [62,63]. The model comprise of three parallel competing pathways in the primary pyrolysis for wood to be degraded to char, tar and volatile. The model and experimental data fits relatively well for temperature range of 230–260 °C. After 260 °C the model fails to fit the experimental data. This was possibly due to the initiation of carbonization reactions which is not accounted in the model [63]. A mathematical model was established for the design and optimization of the patented TORSYPD reactor [54]. TORSYPD is a continuous moving bed reactor designed by Thermya, a French engineering company for the production of biofuel via torrefaction. In this work, the authors have opted to use the Shafizadeh and Chin model for biomass torrefaction process [62]. Coupled with the model for drying and the transport of particles as well as the gas stream, the authors were able to predict good temperature profile of the TORSYPD reactor compared with the experimental data from continuous pilot plant. In a separate work, temperature integral approximation proposed by Agrawal and Sivasubramanian was adopted to estimate the reactivity of thermally treated biomass under the non-isothermal decomposition of biomass for the torrefaction parameters examined [26,64]. The combustibility curve of the torrefied samples was represented by two stages. Kinetic parameters derived indicate that the activation energy of the first stage varies with the residence time while the second stage remains relatively constant. To date the published kinetic studies for torrefaction is mainly focused on model fitting, and furthermore work is limited in the study of the effect of mineral matters towards the kinetic of torrefaction. Future work should look at different approach for kinetic analysis to validate reliability and consistency of the kinetic information as well as examine the effect of mineral matters.

4.2. Densification

Densification is a compacting process to enhance the durability and characteristics of selected material. In torrefaction, briquetting and pelletizing are the two form of densification process opted.

Product densification allows torrefied biomass to be converted into a convenient energy carrier in term of transportation, storage and handling due to its uniform shape and size. ECN's TOP (torrefaction and pelletization) process has succeeded in producing torrefied pellets which has improved durability and hydrophobicity compared with conventional wood pellets. Feedstock variety from woody to herbaceous biomass can be utilized to yield biopellets of analogous physical properties and no additional binder was added in the TOP process. ECN modeling result showed that total production cost of the plant can be reduced due to reduced operating cost of TOP process [65]. In the Topell Energy and 4Energy Invest commercial plant which is under construction, both companies have incorporated pelletization in the plant design [66,67].

In a separate study, pelletization of switch grass was yield undesirable due to the friability introduced to the feed after torrefaction process. The decomposition of hemicelluloses during torrefaction was postulated as the factor resulting in the brittle pellets. Hence, torrefaction and pelletization is proposed to be combined whereby thermal degradation of hemicelluloses will enhance inter-particle bonding [68]. Lignin found in most plant-based biomass acts as binder in densification process [65,69]. It was recommended that lignin and extractive content not exceeding 34% will improve the durability of pellets. Although temperature and pressure are the main parameters for product densification, factors such as particle size, mixing feed and the change in the biomass constituents will need to be considered in the pelletization of torrefied biomass [69].

4.3. Gasification and combustion

Biomass gasification can generally be summarized into four main stages namely drying, devolatization, oxidation and reduction. Through gasification, synthesis gas (syngas) comprising mainly of carbon monoxide and hydrogen are generated. Syngas can then be subject to direct combustion for energy generation or undergo Fischer–Tropsch process to derive synthetic fuel. Torrefaction of biomass as a pretreatment path has been reported as a possible option to reduce production cost in synthesis of Fischer–Tropsch fuels [70]. In a gasification study comparing torrefied pine with untreated pine, a reduction is observed for the synthesis of tar precursors such as acetol and guaicol [71]. The altered composition of biomass subject to torrefaction has been reported to improve the reactivity of the biofuel [33,71]. Reactivity is one of the key factors affecting the sizing of gasifier in reactor design. Higher heat of combustion compared to parent feed indicates that torrefied product has the potential to be used for domestic purposes through direct combustion [33,36]. Although extensive studies have been made on the solid product, limited publications has been made on the utilization of torrefied product in existing thermochemical process.

5. Commercial development

Commercial development of torrefaction is currently in its early phase. Several technology companies and their industrial partners are gradually moving towards commercial market introduction. Table 6 highlights the types of reactor technology adopted by various companies.

Torrefaction reactor design can broadly be classified by the movement of the biomass in the reactor. Reactor design proposed in commercial application can generally be classified as fixed bed, fluidized bed and moving bed.

5.1. Fluidized bed

Topell Energy constructed its first commercial torrefaction plant in Duiven, the Netherlands in June 2010. With a production capacity of 60,000 tons per year, the plant is expected to start producing Topell biofuel in early 2011. Topell applies TORBED Reactor technology, which is a fluidized bed reactor that has a short reaction time and higher heat transfer efficiency. High velocity gas suspends the biomass in the porous support to be in a fluid-like state. This phenomenon allows intense contact between biomass and process gas generating homogeneous particle mixing and uniform temperature gradient.

Table 6
Reactor type for torrefaction [65–67,72–80].

Reactor types	Technology companies
Fluidized bed	Topell Energy
Moving bed	Agri-Tech, Torr-Coal, ECN, 4Energy Invest, Integro Earth, CMI-NESA, Thermya

Topell's commercial plant couples torrefaction with pelletization to produce biocoal pellets that are generated from woody biomass and agricultural waste. The biomass undergoes up to 70% increment in its volumetric caloric density (GJ/m^3). Torrefied pellets can be used as a feedstock for co-firing with coal up to a range of 80%; equating to a 10 times increase in percentage of biomass used [66,74,81].

5.2. Moving bed

Moving bed equipped with mechanical transport mechanism such as multi-hearth, screw or auger reactor and rotary kiln are the more popular reactor choice for torrefaction in the commercial development. Thermya announced in March 2010 the commercialization of its torrefaction process, TORSPYD. A French engineering company, Thermya utilized directly heated moving bed reactor to produce torrefied product known as BioCoal from woody biomass. In the Thermya reactor, biomass feed moving downward is in close contact with countercurrent hot gas stream introduced at the base of the vertical column. The first TORSPYD pilot plant was built in 2007. The BioCoal produced successfully attained less than 1% moisture coupled with retention of 95% initial energy content and 90% of its original mass. Net calorific value of the BioCoal is estimated to be around 20–21 MJ/kg compared to the 7.4–11.4 MJ/kg for untreated crushed wood. In the TORSPYD torrefaction layout, Thermya recommends recycling 4% of the BioCoal produced back into the system to the meet the energetic requirement of the torrefaction column. Thermya is constructing its first commercial TORSPYD torrefaction plant in Spain schedule for completion in late 2011 [72,73].

Belgian based renewable energy company, 4Energy Invest, incorporated a torrefaction facility at its biomass co-generation power plants in Amel, Belgium. The biomass torrefaction unit is a moving bed reactor built in collaboration with Stramproy Green Technology. The building of the torrefaction plant, Amel III was initiated in February 2009 and was reported to produce torrefied wood chips while its pelletization process is currently in commissioning. 4Energy Invest has achieved torrefied product of almost equivalent energy density to the coal used in its utilities. Production capacity of the facility is estimated to be 40,000 tons per annum for electricity generation facilities and charcoal for barbecue purposes [67,82,83].

Torr-Coal Group has developed its own torrefaction technology known as Torr®Coal technology using a revolving drum oven as torrefaction reactor with continuous input capacity of 7 tons/h. The construction of the first Torr-Coal production facility with a production capacity of 36,000 tons was launched in August 2009 in Limburg, Belgium. Operating temperature range for Torr®Coal is in the regime of 280–300 °C with product of 70% mass yield and 90% energy content of the original feed. Feedstock for Torr-Coal can be both woody biomass and Secondary Recovered Fuel (SRF). SRF is

typically fuel material derived from corporate waste or household waste stream for energy generation. The lower calorific value of the obtained product is in the range of 18–20 MJ/kg. The design for Torr®Coal involves subsequent mechanical process of size reduction and sieving to prepare the torrefied product for Torr-Coal's patented dechlorination and desulfation step. Torr-Coal Technology states that 90% of the chlorine and 30% of sulfur can be removed as a result to produce torrefied solid fuel that meets customer requirement in term of chlorine and sulfur content [75,84,85].

The torrefied product from the temperature range of 240–270 °C is able to achieve a heating value range of 22.08–25.57 MJ/kg. Integro Earth Fuels based in North Carolina joint venture with American Refining Group (ARG) is converting the data obtained from its pilot plant onto the design of its first commercial torrefaction. The 50,000 tons per year facility located in Roxboro, North Carolina utilizes Turbo-Dryer Reactor. Biomass feed enters the rotary dryer from the top and rotating circular trays repetitively swipes the biomass top-down after each revolution. Hot process gas circulating within the enclosed vessel along with the continuous mixing provides constant moisture removal and subsequently torrefaction [86]. Integro Earth Fuels is currently finalizing the design of its first commercial plant and has plans to build 10 additional facilities in the upcoming six years [76,77,87].

In June 2010, Vattenfall and Energieonderzoek Centrum Nederland (ECN) signed partnership contract to upscale the torrefaction technology which has been extensively researched in ECN. After the successful long duration test of 100 h on ECN's pilot installation, a demonstration plant of capacity 5 ton/h is currently under development utilizing moving bed reactor as heart of the torrefaction facility. BO2 technology proposed by ECN comprises of drying, torrefaction and pelletization to obtain BO2 pellets. The generated BO2 pellets have improved energetic value up to 30–80% compared to wood pellets. In term of feedstock, woody biomass will allow the retention of 70% mass and 90% of the initial energy content. Agricultural residue and waste derived fuels such as refuse-derived fuel (RDF) can possibly be applied to the torrefaction unit [78,88].

Agri-Tech Producers offers a 5 tons/h capacity torrefaction unit, Torr-Tech 5.0. This unit equipped with the technology developed by North Carolina State University operates in the range of 300–400 °C. It is capable to handle feedstock of more than 40% moisture content. Feedstock for Torr-Tech 5.0 can range from wood chips to bio-crops such as switch grass and mischantus. Energy value of generated product is approximately 23.24 MJ/kg with moisture content of 10%.

The French joint partnership of Agence Nationale de la Recherche (ANR), TORBIGAP, Cockerill Maintenance & Ingénierie (CMI) has proposed the use of multi-hearth torrefaction reactor. Multi hearth reactor offers the benefit of flexible process control and operating range as rabble arms attached to the central shaft agitates and move biomass feed from one hearth to the next. This promotes the heat transfer efficiency of multi-hearth reactor and allows better control of retention time within reactor [80,89].

6. Conclusion

The torrefaction of biomass as a pre-treatment step has the potential to contribute to the world energy demand. In the recent years, torrefaction studies on various biomass feed associated with fuel properties has shown promising result. However due to the complexity and variety of feed that can be introduced to the process, indicative expressions to define the process parameters has yet to be derived. The polymeric structure of biomass has been closely associated with the torrefaction process output. Detailed investigation on the potential of biomass polymeric structure in the torrefaction process is limited. Future work can look into the possibility of deriving indicative parameter to define process parameter for torrefaction based on the polymeric structure of the feedstock. Torrefaction process generates solid, liquid and gaseous product, and extensive studies have been done on the solid torrefied product. The research on the by-product (gas and liquid) has been minimal. Focus should be made on the possibility of utilizing the by-products to improve the overall torrefaction process efficiency. Kinetic analysis for torrefaction is majorly concentrated on model fitting. It is proposed that future work should examine different kinetic analysis approach to validate reliability and consistency of the kinetic information. In addition, the effect of mineral matters on the torrefaction kinetics is proposed to be investigated as well.

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